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Final Scientific Report AFOSR GRANT 79-0006

"Turbulent Boundary Layer Structure and Drag Reduction"

by

M. T. Landahl

and

S. E. Widnall

(Principal Investigators)

SUMMARY

During the grant period the research work has progressed along the following lines: i) development of a localized three-dimensional disturbance in a shear flow; ii) exploration of new instability modes for inviscid and viscous shear flows iii) analysis of polymer drag reduction mechanisms; and iv) experiment to study spanwise growth of transition spots in a plane Poiseuille flow.

1. Introduction

The fundamental idea underlying the research work under this project and its predecessors is that the mechanism of boundary layer turbulence could be understood on basis of how disturbances are generated and maintained in a shear flow. Hence, the study of hydrodynamic instability mechanisms would be of central interest in this connection. Following such ideas, Landahl (1975) proposed a two-scale model for the generation of turbulent bursts in the wall region, in which large-scale disturbances were hypothesized to create conditions, in a quasi-cyclical manner, for the onset of small-scale secondary instability leading to break-down of the large-scale coherent motion.

The mixing due to the small scale motion would set off a new large-scale disturbance, and the process would then repeat itself. In Landahl (1978) it was shown with the aid of a simplified model that a three-dimensional disturbance of large horizontal scale in an inviscid shear flow would with time develop a strong internal shear layer. The mechanism involved was identified as stretching of spanwise mean vorticity. The continued work has been primarily concerned with the details of the internal shear layer formation, and the relation of the three-dimensional disturbance development to hydrodynamic instability mechanisms.

2. Development of a Three-dimensional Disturbance in a Shear Flow

A calculation method has been developed to determine the evolution of a localized three-dimensional disturbance in an inviscid parallel shear flow. The method uses Lagrangian coordinates (coordinates fixed to fluid elements) and a series expansion in time to account for the effects of pressure in accelerating or decelerating a fluid element. This represents a further extension of the method presented by Landahl (1978). A computer program has been developed for treating the evolution of a three-dimensional disturbance in a plane Poiseuille flow. The disturbance is assumed to have a large horizontal scale compared to the distance between the walls. This allows one to neglect the variation of pressure across the channel which considerably simplifies the numerical calculation. An initial three-dimensional "pancake"-like disturbance for which preliminary computations have been carried out is illustrated in Figure 1. The disturbance amplitude was chosen to be quite large namely having a maximum spanwise velocity amplitude equal to 0.42 times the maximum velocity in the Poiseuille flow, so that non-linear effects could be brought out.

Figure 2 shows the vorticity distribution along the centerline Z = 0, at a non-dimensional line of $t^+ = 7$. It is seen that the vorticity has developed maxima for positive x/l_2 and y/l_2 about .2 (l_2 being the distance between the walls) indicating the presence of an inflection point and thus the possibility of secondary instability. Beacause of the expansion in terms of time, the calculation method is restricted to times which are small compared to the time it will take the disturbance to be converted downstream a distance equal to its streamwise length.

The work on this problem continues and will be reported in a forthcoming doctoral dissertation by John Russell. The effects of viscosity, which were ignored in the above analysis, also become important for long times, especially in the region near the wall. Viscosity may be included in the full linearized treatment of the initial -value problem for a parallel shear flow by using Fourier-Laplace transformation techniques as demonstrated by Gustavsson (1979).

This analysis has shown that a disturbance evolves both in terms of waves and in terms of a transient. The presence of a transient, or continuous spectrum, was suggested by Mack (1976) because the discrete eigenvalue spectrum of the Orr-Sommerfeld equation is finite. The eigenfunctions of this new mode of motion was calculated by Grosch & Salwen (1978), and the amplitude was found to be practically zero within the boundary layer. These calculations were for two-dimensional disturbances. However, it was pointed out in Gustavsson (1979) that the transient is the only component that can represent structures infintely long in the streamwise direction. This property has been exploited in Hultgren & Gustavsson (1980), where the exact solution of the transient for such long structures is presented.

The development for small times of the different velocities show a similar behavior as in the inviscid problem (Ellingsen & Palm, 1975), i.e., the vertical velocity remains essentially constant, whereas the streamwise velocity grows linearly in time. Eventually, the viscosity will make the disturbance decay.

In addition to the time-behavior, the spatial distribution of the transient has been investigated. It has been found that the transient may have large amplitudes within the boundary layer provided the disturbance is almost parallel to the mean flow. This strongly indicates that the transient is associated with the streaks that have been observed in boundary layer flows.

3. New Modes of Hydrodynamic Instability

3.1 Parallel Shear Flows

By studying the variation of the streamwise integral of a localized three-dimensional disturbance in a parallel inviscid shear flow Landahl (1980) showed that an inviscid shear flow is algebraically unstable to a large class of such disturbances in the sense that the kinetic energy of the disturbances grows linearly with time for large times. The explanation is that the streamwise perturbation velocity will tend to a finite value in a frame of reference convected with the mean flow, whereas the streamwise dimension of the disturbed region will grow linearly with time. This result may have implications for understanding the observed sensitivity of a boundary layer to spanwise irregularities, and in particular for the tendency of wall shear flows to develop longitudonal streaks.

A related mechanism has been discovered for viscous shear flows leading to algebraic growth for small times followed by eventual exponential decay.

The mechanism, identified as reasonant forcing of vertical vorticity by damped Tollmien-Schlichting waves, has been investigated in plane Couette flow (Gustavsson & Hultgren, 1980), and in plane Poiseuille flow (Gustavsson, 1980). In plane Couette flow, the resonance occurs at a phase speed equal to the center line speed. For each wave number there is a certain Reynolds number above which the resonance occurs. As the Reynolds number increases, the aspect ratio of the resonantly driven waves increases, thus indicating that streaky structures may be formed.

In contrast to plane Couette flow, for plane Poiseuille flow the resonance occurs only for certain wave numbers and for certain values of the product of the streamwise wave number and the Reynolds number. The critical Reynolds numbers at which the resonances start to operate are all very small. At the transition Reynolds number ($\sim$1000) at least eight such resonances have been identified. Large amplication of the resonant waves can cause nonlinear phenomena to become important. This problem is currently under investigation and will be reported in Benney & Gustavsson (1980).

3.2 Instability of Vortex flows

The inviscid instability of a row of two-dimensional vortices has been investigated by Pierrehumbert (1980) with partial support under this research program. This problem is of importance for the understanding of shear flow turbulence since vortex interaction mechanisms such as pairing instabilities and three-dimensional streak formation has been suggested to play an essential rôle in turbulence production.

The pairing interaction has been implicated in shear layer growth (Roshko,1976,presents a good review of the relevant observations) and streak formation has been associated with generation of small scale turbulence and enhanced mixing (Bernal, et. al. 1979). In addition, a three-dimensional version of the pairing instability has been implicated in the generation of coherent three-dimensional structures (Browand and Troutt, 1979). A careful examination of the data available on the structure of shear layer vortices indicated that the observed arrangement of vortices could be accurately represented as either a nearly parallel flow or a row of point-like vortices, although the observed vorticity distributions do resemble certain steady solutions to the Euler equations in two dimensions. Hence, the stability problem was approached via the numerical solution of the partial differential equation eigenvalue problem in two dimensions which appears in the formulation of the linear stability problem of a two dimensional steady flow.

An efficient spectral code for the solution of the problem was written and several cases relevant to the observed states of the shear layer were calculated. The main results are as follows: (1) the shear layer has a subharmonic two-dimensional instability which resembles pairing. The predicted growth rates are in excellent agreement with the observed growth rates. (2) the pairing instability can exist in a three-dimensional form, whereby the vortex pairs with its neighbor to the right at one spanwise station, but with its neighbor to the left at another spanwise station. This instability has a cutoff for short spanwise wavelengths which is fully consistent with observations. (3) In addition to the subharmonic instabilities there is a harmonic instability which is most unstable at spanwise wavelengths comparable to the vortex core size, although the shortwave cutoff for this instability is weak.

The maximum growth rate is comparable to that of the pairing instability, and the mode has a number of features that make its association with the observed streak pattern plausible.

4. Studies of drag reduction mechanisms

In Landahl (1973) it was suggested that long-chain polymers and other drag reduction additives may act by stabilizing small-scale inflectional instabilities and thereby interrupt the turbulence production cycle. Stability calculations employing a simplified rheological model for the additive consisting of aligned suspended rigid rods as proposed by Batchelor (1971) shows that two-dimensional wave-like disturbances are strongly stabilized by the additive. However, recent calculations by Tinoco and Bark (1980) show that for three-dimensional waves the additive may actually be destabilizing. Since observations clearly show that the small-scale eddies are suppressed, alternate mechanisms of how additives change the turbulence need to be considered.

5. Experimental Study of Transition Spot Spreading

From linear Tollmien-Schlichling wave theory one can show that small disturbances have a larger spanwise spreading angle in a plane Poiseuille flow ($\approx 16°$) than in a Blasius boundary layer flow ($\approx 10°$). Since the observed angle of spreading of a transition spot in a Blasius boundary layer is close to the linear wave spreading angle, it was hypothesized that a turbulent spot in a plane Poiseuille flow would have an angle of spreading close to the linearized value. To test this idea, an experiment has been set up to study the propagation and spreading of a turbulent transition spot in a plane flow between two parallel walls. To be able to use visualization techniques to follow the development of the spot the walls are made out of plexiglass. The apparatus has been designed and built and measurements will be started during the research period of the continuation grant.

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+ Prepared under present Grant.

++ Prepared under previous AFOSR Grants.

FIGURE 1 . VELOCITY FIELD OF INITIAL EDDY

$$u_0(x,y,z) = 4U_{MAX}\left(\frac{y}{l_2}\right)\left(1-\frac{y}{l_2}\right) \qquad w_0(x,y,z) = g_0\left(\frac{x}{l_{13}}\right)e^{-\left(\frac{x}{l_{13}}\right)^2}\left(\frac{z}{l_{13}}\right)e^{-\left(\frac{z}{l_{13}}\right)^2}g'\left(\frac{y}{l_2}\right)$$

$$v_0(x,y,z) = -g_0\frac{l_2}{l_{13}}\left(\frac{x}{l_{13}}\right)e^{-\left(\frac{x}{l_{13}}\right)^2}\left(1-2\left(\frac{z}{l_{13}}\right)^2\right)e^{-\left(\frac{z}{l_{13}}\right)^2}g\left(\frac{y}{l_2}\right) \qquad g'\left(\frac{y}{l_2}\right) = \sin\left(\frac{2\pi y}{l_2}\right)\sin\left(\frac{4\pi y}{l_2}\right)$$

$l_{13} \equiv 5l_2$

$g_0 \equiv -3U_{MAX}$

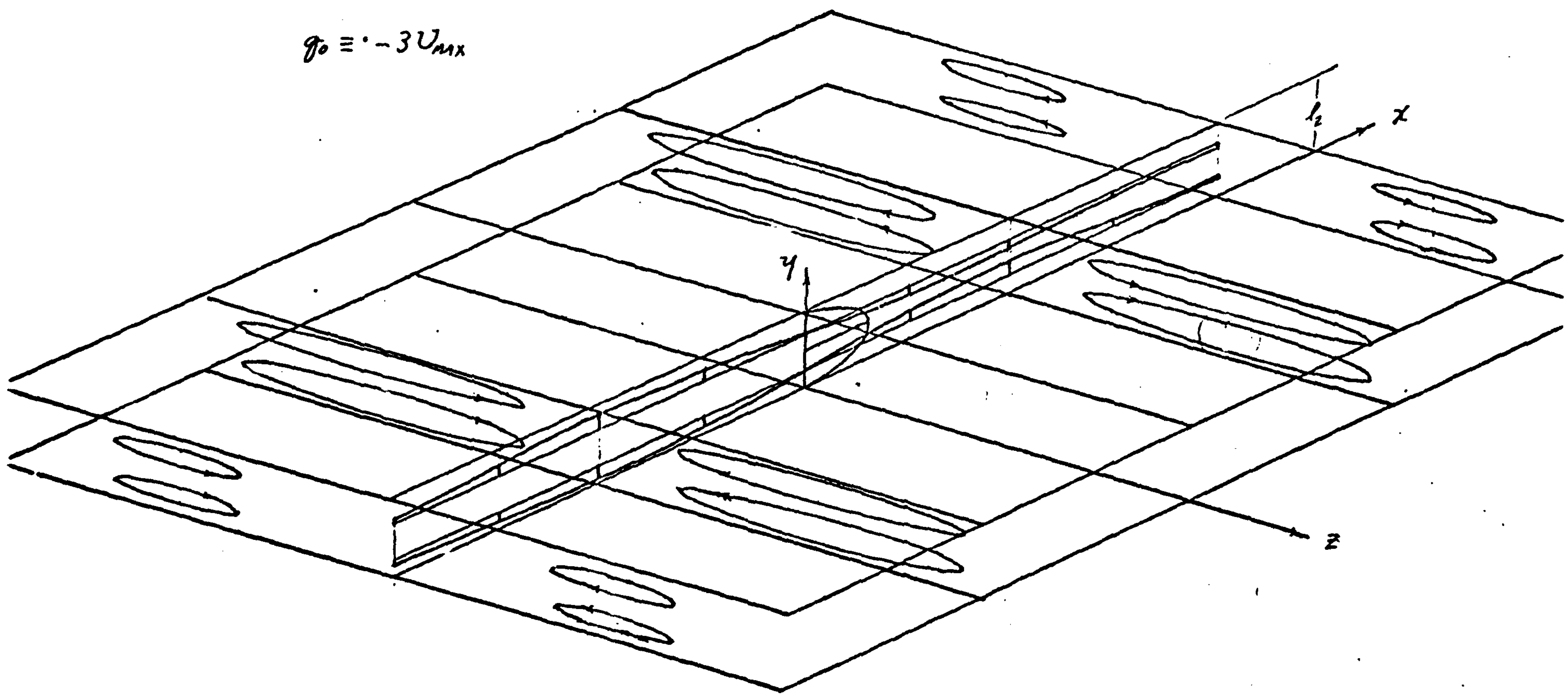
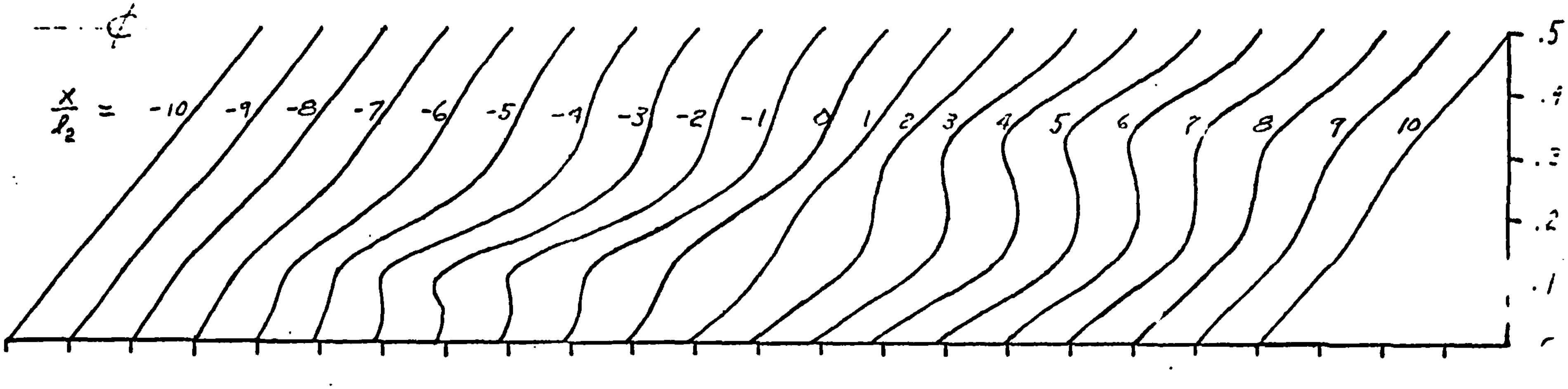


FIGURE 2
PROFILES OF SPANWISE VORTICITY FOR LOWER HALF OF CHANNEL (SYMMETRIC DISTURBANCE)
$t' = 7 \qquad z = 0$



NOTE: $\omega_3 \equiv 0$ ON CENTERLINE FOR ALL PROFILES